THE DEVELOPMENT OF SOLAR SAIL PROPULSION FOR NASA SCIENCE MISSIONS TO THE INNER SOLAR SYSTEM

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ABSTRACT

This paper examines recent assessments of the technology challenges facing solar sails, identifies the systems and technologies needing development, and the approach employed by NASA's In-space Propulsion Program in NASA to achieve near term products that move this important technology from low technology readiness level (TRL) toward the goal of application to science missions in near earth space and beyond. The status of on-going efforts to design, build, and test ground demonstrators of alternate approaches to structures (inflatable versus rigid), membrane materials, optical shape sensing, and attitude control will be presented along with planned future investments.

Background

Solar sails are a near term, low thrust, propellantless propulsion technology suitable for orbital maneuvering, station keeping, and attitude control applications for small payloads. Furthermore, these functions can be highly integrated, reducing mass, cost and complexity. The solar sail concept is based on momentum exchange with solar flux reflected from a large, deployed thin membrane. Thrust performance increases as the square of the distance to the sun. In comparison to conventional chemical systems, there are missions where solar sails are vastly more and less economical. The less attractive applications involve large payloads, outer solar system transfers, and short trip times. However, for inclination changes and station keeping at locations requiring constant thrust, the solar sail is the only economical option for missions of more than a few weeks duration.

Solar Sails were identified in a study process performed under the auspices of the In-Space Propulsion Technologies program and funded by NASA's Office of Space Flight. It is the purpose of the ISP program to advance Mid-level maturity propulsion technologies to a level needed to be selected and used in NASA robotic science missions. Figure 1 illustrates the regime of investments made the ISP program.

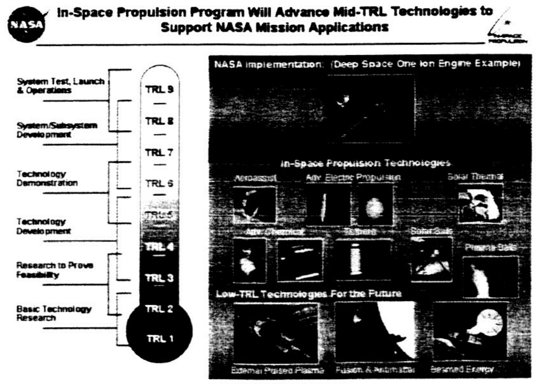


Figure 1.

Mission Need for Solar Sails

NASA's Sun-Earth Connection program under the Office of Space Sciences has published an evolutionary vision for utilizing solar sails to advance their science goals.[1] Shown in Figure 2, this mission need roadmap starts with a modest-sized near term technology demonstration mission and ends with a very large, very gossamer interstellar probe.

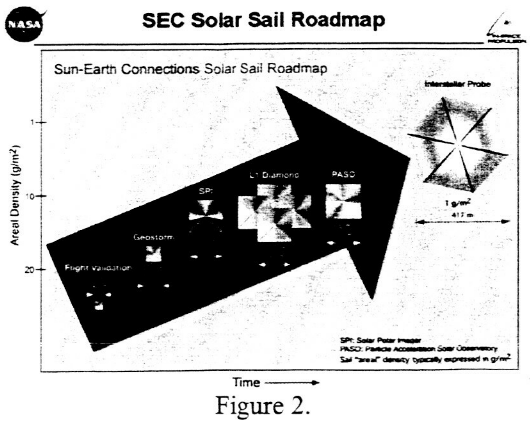


Figure 2.

Geostorm, a space weather related mission is of less interest now than when the report was written. In the interim, NOAA has decided to press forward with more conventional propulsion options. The nearest term project pulling the sail technology is the Solar Polar Imager (SPI), followed by the L1 Diamond and the Particle Acceleration Solar Orbiter. Each of these is addressed below. The new human exploration mission initiative announced by President Bush recently has a component of in-space technology development, but the decision has been made keep ISP focused toward the development of primary propulsion for robotic science missions rather than delivering humans or cargo to the moon and Mars.

Solar Polar Imager

Missions that have to make an inclination change are known to be challenging for chemical rockets. In the equation below, V is the starting orbital velocity and θ is the plane change angle.[2] Equation (1) gives the standard relationship for calculating the effect of a velocity change on an orbit.

$$\Delta V = 2V \sin(\theta/2) \qquad [1]$$

This assumes the thrust is directed along the angular momentum vector of the orbit. For chemical systems, the small penalty resulting from the instantaneous change in the direction of the angular momentum vector can generally be ignored. For solar sails, the changing orientation between the angular momentum vector and the solar vector would have to be factored in to the maneuver. The mass penalty for carrying propellant to do these type maneuvers impulsively is high and is one of the strong justifications behind the assessment that solar sails are an enabling technology for the Solar Polar Imager (SPI). The science objectives of this mission include measurement of the Sun's polar irradiance and magnetic field, imaging the full effect of Coronal Mass Ejections (CMEs) and evolution on the full 3-D. corona, and linking of variations in the high latitude heliosphere to surface conditions. The mission profile calls for travel in the ecliptic then taking up a 0.48 AU heliocentric circular orbit inclined 60 degrees. Mission designers have estimated a sail in the vicinity of 150 meters across will be needed.

A study by Harris[a] established the initial mission concept. Later studies by Neugebauer[b], and Ayon[c] et al, refined the science objectives and the mission and system design. Figure 3 represents the most current flight system concept. The SPI mission concept was recently selected (Liewer[d]) for further refinement under the Vision Mission NASA Research Announcement.

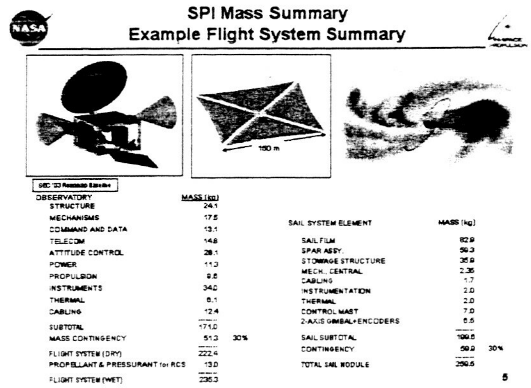


Figure 3.

L1 Diamond

The L1 Diamond mission will make use of a solar sail's unique propellantless thrust nature to hover in space sunward of the Earth-Sun L1 libration point. Conventional spacecraft can be parked in a relatively small region of space that will require only occasional station-keeping thruster firings. The always-on thrust of a sail can be used to park a science experiment in a much larger volume of space. The vantage points available to science are only a function of sail size and lightness and a relatively large range of locations is reachable within the near term state-of-the-art. L1 Diamond is a constellation of four spacecraft cooperatively and concurrently gathering data to validate models of processes in-situ through a three dimensional sample region of space. See figure 4.

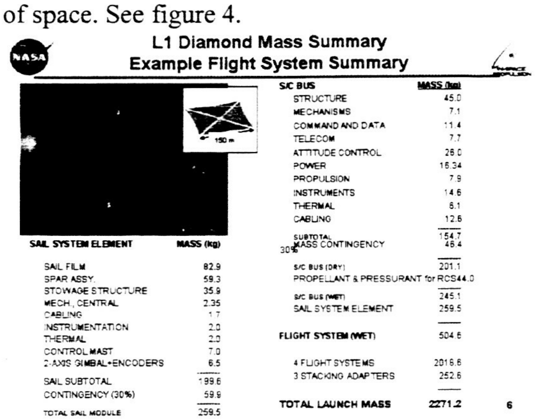


Figure 4.

L1 science objectives are to measure the properties of solar-wind turbulence (as seen in density, velocity vector and magnetic field) as a function of separation in space and time, ranging from the dissipation scales of hundreds of kilometers to the outer scale of millions-of-kilometers. Direct measurements of the possible spatial symmetries of the turbulence is also desired along with measurements of the spatial variation in propagating waves, shocks and other disturbances in the solar wind. Another objective is the discovery of associations of the turbulence with suprathermal and energetic particles. The Delta IV Launch Vehicle has been suggested to put the spacecraft into a ballistic transfer from Earth to an Eart-Sun L1 halo orbit which would take about 90 days. The solar sail would accomplish the transition from the initial libration point to the various constellation stations. Three spacecraft will be in a triangle formation whose centroid is 280 - 500 Earth radii sunward of Earth on the Sun-Earth line. A fourth is located above the ecliptic plane. Continuous solar viewing for at least three years is needed.

Particle Acceleration Solar Orbiter (PASO)

Finally, PASO will drive the next development of the next class of solar sails to transfer a science instrument payload to a very close solar orbit (0.169 AU). See figure 5. The PASO measurement strategy is to capture high resolution images of high energy solar flares allowing the detection of composition. The mission will also employ a neutron spectrometer and a gamma ray spectrometer. Solar wind and magnetic field instruments will also be included. The science objectives are to understand particle acceleration mechanisms, distinguish between flare and shock accelerated particles, and study the active region evolution. The mission concept begins with a Delta launch and then transfer from 1 AU to a 0.169 AU circular solar equatorial orbit with a period of 25.4 days. The transition to the final lower solar orbit will take three years during which active CME Source regions will be in continuous view. Mission scince operations will continue another 4-5 years in the final orbit.

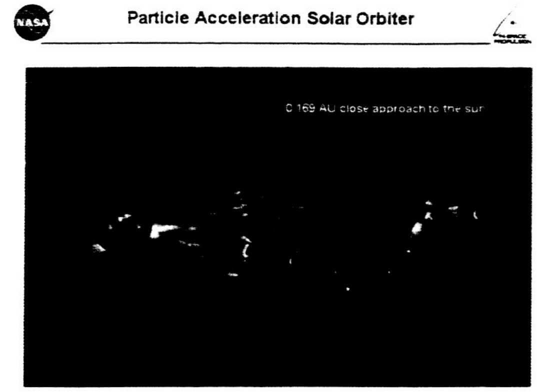


Figure 5. PASO Mission Concept [ref 1]

Other Missions for solar sails

Since the thrust of a solar sail is small, it does not suit missions involving massive payloads or short trip times. However, if a very high ultimate velocity is needed, such as fast flyby missions to the outer planets or extra-solar system destinations, solar sails can be the only feasible alternative. Although solar pressure has greatly attenuated at those distances, the long trip time out at constant thrust integrates to a considerable total velocity increase. A study by Price and others showing how the flight times for solar sails to the heliopause is less than half of the most efficient reaction jet rockets.[3] See figure 6.

Recent research by Taylor and Matloff suggest that the outer planetary stopover missions for small robotic science packages may also be a possibility utilizing a bi-modal sail. The concept is an unconventional, high altitude pass, low dynamic pressure aerobraking maneuver. Gossamer mass properties could enable trajectory shaping with relatively non-stressing (small thermal or pressure shocks) aerobrake maneuvers. Sail and boom loads for a Titan aerocapture might only be a fraction of what the same sail would encounter from solar pressure in earth orbit.[4]

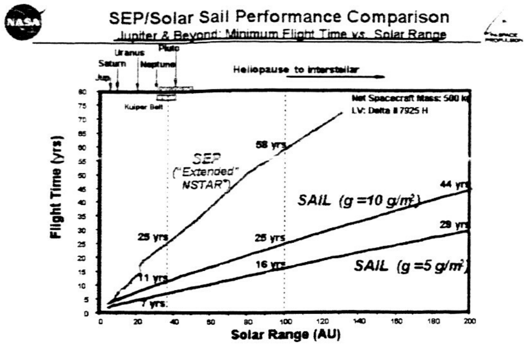


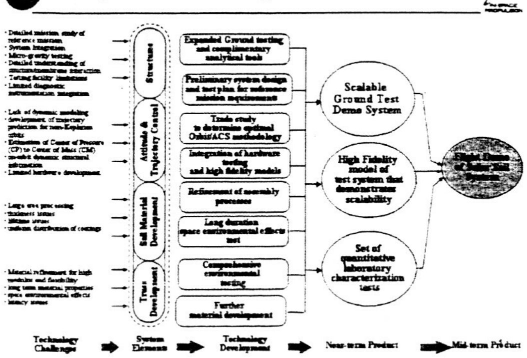
Figure 6. SEP/Solar Sail Performance Comparison

The Interstellar Probe Mission will measure, in situ, the properties and composition of interstellar plasma and neutrals, low energy cosmic rays, and interstellar dust. The technology challenges are great. Mission designers believe at least a 200-meter highly reflective sail will be needed with an areal density of less than 1 g/m2 - beyond any known technology. In space Propulsion has classified this as an Emerging Technology.

Technology Challenges

In January of 2002, the results of a panel of experts from industry, academia, and the government was formed to assess the state of the art of solar sail technology and provide guiding inputs for the In-Space Propulsion Program to use in formulating a plan to bring the maturity of solar sails to TRL 6.[5] This level is defined as a full system validated in a relevant environment. The delineation between it and the next level is use in a space mission. The result of the panel is summarized in Figure 7.

Figure 7. Solar Sail Technology Assessment Group Roadmap



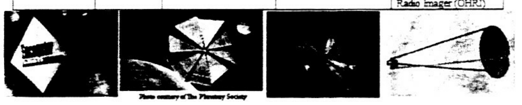
A similar activity was conducted in March of this year.[6] The results largely validated the previous assessments and indicated that the state of the art had been improved dramatically, was maturing in the proscribed directions, and was addressing the priority needs in a developmental approach (i.e. roadmap) consistent with the recommendations of the technical community. Members of the Technology Assessment Group (TAG) included Government, Industry, and Academia. Export control regulations precluded foreign participation.

Formulation of a Technology Development Program

The Solar Sail Propulsion (SSP) technology area was formed within ISP to accomplish the program objectives for solar sails utilizing the TAG's input. Organizing the topic area began with identifying that four different solar sail types existed, each having specific characteristics (listed in figure 8) that identified a common class of missions and peculiar technology requirements. The first class is indicative of some validation flight concepts and can be said to have some TRL 7 flight heritage through the Russian Znamiya program and the NASA Inflatable Antenna Experiment (IAE). The last mission type is one requiring extremely lightweight systems for which there are no TRL 3 candidates. The other two applications are the focus of the ISP program. In defining a roadmap for those, it logically fit a serial effort to develop first the 1 AU sail, and then extend the technology to the harsher environments at less than 0.25 AU from the sun.

Figure 8. Sail Technology Classes

Mission Class	Timeline	SOA	Technology Challenges	NASA Mission Application
GEO/GTO Short Life	Past/Now	Encounter(?), Cosmos, ST-7, Znamya, Inflatable Antenna Exp	AO, radiation belts effects, high GG torques	None
1 Au	**Near Term**	**ISP Ground Demo, ST-5 Geostorm**	**Validation in a space environment, Infusion into mission applications**	**L1 Diamond Solar Polar Imager (SPI)**
<0.25 Au	Mid-Term	Mission analysis, Future ISP work	Materials environments, Thrust vector range, Lightweight system, 100s m system scale size	Particle Acceleration Solar Observatory (PASO) Titan Explorer Saturn Ring Observer
Extra Solar	Far-Term	Mission concept analysis, Gossamer, Encounter(?)	Ultra-lightweight system Integrated system architecture Sub to kilometer system scale size	Interstellar Probe (ISP) Geospace System Response Imagers (GSRI) Outer Heliosphere Radio Imager (OHRI)



Budget limitations drove the need to focus technology development on the most near term classes. A convenient discriminator between the classes is the region of space in which they are intended to support missions. This logic led to the establishment of the following mission statement:

1. Raise solar sail technology as a primary propulsion system for inner solar system NASA missions to TRL 6

2. Solar sail propulsion technology shall be scalable to inner solar system NASA missions

3. Attain closest approach to TRL 6 possible on the ground by the end of FY06

An investment strategy was derived utilizing the guideline that at least 75% of the program investment would go to competitively selected efforts. The implications drove the procurement of the 1 AU sail in three annual NASA Research Announcement cycles. The next inner solar system sail class would then follow in three additional cycles. Figure 9 illustrates the SSP roadmap.

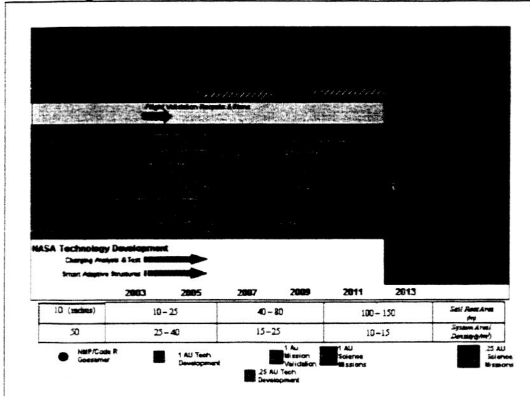


Figure 9.

Looking across roadmap at the mission concepts, a survey of the two key sail design parameters, areal density and root area indicates the level of material science and fabrication knowledge needed. Revealed in the evolutionary path for the structural solution are evolution steps at plateaus around 15meters, 70 meters, and 150 meters.

Future plans

NASA plans a vigorous program to bring solar sails to prepare solar sail technology for validation and flight implementation in the missions shown

Summary

The objective of the SSP technology area investment is to develop solar sail technology to the level of validating a system in a relevant environment. High value science missions have been identified that require solar sails. Experts have met and defined the development needs and products, and a time phased program has been laid out to prepare NASA to go places only sails can go.

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